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LIMITING FACTORS IN TACTICAL TARGET ACQUISITION,(U)

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(6) LIMITING FACTORS IN TACTICAL TARGET ACQUISITION

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I. INTRODUCTION

Current defense concepts contemplate the use of tactical aircraft to counter an attack by armored vehicles. Because SAM defenses must be assumed to be present, the tactic of choice is continual low altitude, high speed flight. This flight tactic, however, makes target acquisition difficult because of the limited time available for search. Correspondingly, this implies a low probability of being able to convert to a first pass attack. The problem is especially severe at night and/or during degraded visibility conditions. Under these conditions FLIR sensors offer the best means for acquiring targets. Nevertheless, because the field of view of a typical high resolution FLIR is of the order of a few degrees, the observer is handicapped by "tunnel" vision as he searches for the target. In a dense clutter environment there is a significant probability that the target will not be seen in time to permit a first pass attack, assuming that it is seen at all. Since night operations are believed to be an important part of Soviet offense doctrine, it is important to determine how well FLIR sensors will permit tactical air to function during night or degraded visibility conditions.

The crucial part of the target acquisition problem is the performance of the observer, and it must be immediately admitted that we have very little understanding of how an observer actually searches for a target in clutter. As a general statement of principle, an experimental rather than a theoretical approach is to be preferred when dealing with target acquisition problems involving an observer. As a

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practical matter, however, we must recognize that the experimental approach by itself is too difficult and costly to be pursued at any length. Hence, theoretical analyses, however uncertain their results may be at present, are a practical necessity. Given a set of analytical results, a minimal program of experiments can then be designed to test its main conclusions.

This paper summarizes the results of a theoretical analysis of the probability of acquiring vehicle-size targets by a FLIR-equipped observer in a low altitude, high speed aircraft.[1,2] Two scenarios are considered: (1) an attack against a single target whose position is approximately known, and (2) an attack against a frontal array of targets. In the first scenario the aircraft flies a straight line course to the predicted position of the target. The observer searches for the target in the vicinity of its predicted position. In the second scenario, the general location and orientation of the front are considered to be known together with an estimate of the average spacing between vehicles. However, nothing is known about the location of individual targets. The aircraft is assumed to fly a straight line course which perpendicularly intersects the long dimension of the array. The observer uses the so-called "pushbroom" sweep search mode as the aircraft crosses the array. In this search mode the sensor's line-of-sight is fixed relative to the aircraft. The observer is

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[1] Manuscript in preparation by the author on FLIR-aided target acquisition using localized search.

[2] Manuscript in preparation by the author on FLIR-aided target acquisition using sweep search.

confronted with a continual stream of objects passing through the sensor's field of view and his task is to spot a target when it appears. Because the array is crossed in a perpendicular direction, there is effectively only one chance to acquire a target in a single pass.

II. LIMITING FACTORS

The probability of acquisition depends upon four probabilities as follows:

1. The probability that the desired target is within the sensor's field of view.
2. The conditional probability that there is a clear line-of-sight to the target.
3. The conditional probability that the observer looks at the displayed target.
4. The conditional probability that the observer is capable of detecting the target when he looks at its displayed image.

The term "detection" as used above is to be understood in a generic sense. Depending upon the particular acquisition criterion, it may signify either (1) detection of an object of unknown classification, (2) recognition of an object as belonging to a particular class, or (3) identification of an object as a particular member of a particular class.

PROBABILITY THAT TARGET IS IN FIELD OF VIEW

Single Target Scenario

We assume a symmetrical Gaussian distribution of the target's location with respect to the center of the sensor's field of view. If r and θ denote the polar coordinates of a point on the ground, and

If σ denotes the uncertainty in the target's radial position due to navigation errors, etc., then the probability P_F that the target is within a circle of radius r is simply

$$P_F = 1 - e^{-\frac{1}{2}(r/\sigma_T)^2} \qquad (1)$$

The specific calculations described here assume an rms position uncertainty of 0.1 km.

Multiple Target Scenario

The probability of interest for the multiple target scenario is the probability that at least one target passes through the sensor's field of view. If the average spacing between targets is denoted by s, and if the number of targets contained in a given swath width is assumed to have a Poisson distribution, then the probability that at least one target is contained in a swath width x is simply

$$P_F = 1 - e^{-x/s} \qquad (2)$$

The swath width is the product of the viewing range R and the azimuthal width of the sensor s field of view. Thus, if the observer concentrates his attention at short ranges, only a narrow swath is seen and there is a correspondingly low probability that a target will be encountered.

An average spacing of 0.1 km between targets is assumed in the calculations.

PROBABILITY OF A CLEAR LINE-OF-SIGHT

Statistics on terrain masking as a function of altitude have been compiled in the form of a handbook.[3] An example of the statistics for rolling farmland terrain with close forests is shown in Fig. 1. An approximate fit to any particular curve can be made by an expression of the form

$$P_{LOS} = 1 - e^{-(c_h/R)} \qquad (3)$$

where P_{LOS} is the cumulative probability of a clear line-of-sight to a range R, and c_h is an empirical constant which depends upon the altitude. The fits provided by this expression for interpolated altitudes of 200 ft and 500 ft using the values $c_h = 1.8$ km and $c_h = 4.3$ km, respectively, are shown as dashed curves.

PROBABILITY THAT OBSERVER LOOKS AT DISPLAYED TARGET

The conditional probability of a successful search, i.e., the probability that an observer who is capable of detecting the target finds it in the display, is assumed to follow an exponential law as in Bailey's original work on visual target acquisition.[4] This assumed behavior can be shown to be equivalent to a random search without memory.[5] The present formulation, however, describes the clutter in

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[3]Burge, C. J. and J. H. Lind, *Line-of- Sight Handbook*, Naval Weapons Center NWC TP 5908, China Lake, California, January 1977.

[4]Bailey, H. H., *Target Detection Through Visual Recognition: A Quantitative Model*, The Rand Corporation, RM-6158-PR, February 1970.

[5]Feller, W., *An Introduction to Probability Theory and Its Applications*, Vol. 1, Wiley and Sons, Inc., New York, 1957, p. 411.

terms of the number of confusing objects rather than in terms of Bailey's empirical congestion factor. The assumed analytical form for the observer's search behavior is

$$P_S = 1 - e^{-\frac{k(t/t_d)}{N_c}} \qquad (4)$$

where P_S is the probability that the observer looks at the target within an elapsed time t, t_d is the average time required to decide whether a particular object is the target, N_c is the number of confusing objects in the display, and k is a constant established by psychophysical experiments.

Psychophysical experiments by Boynton and Bush[6] and others[7] suggest a value of k between 6 and 8. Accordingly, a value of k = 7 is assumed. The decision time t_d presumably depends upon the characteristics of the target, the similarity of the false targets to the desired target, and the decision criterion imposed by the costs of incorrect decisions. Decision times which are several times longer than the fixation time of the eye may well be required in some instances. If the decision criterion is assumed to correspond to shape recognition as in discriminating between a tank or a truck, for example, a capable observer might be able to make a decision in approximately a single visual fixation time. A single fixation should be adequate for the generally easier

[6] Boynton, R. M., and W. R. Bush, "Recognition of Forms Against a Complex Background," *JOSA*, Vol. 46, No. 9, September 1956, pp. 758-764.

[7] Miller, G. A., "The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information, *Psychological Review*, Vol. 63, No. 2, March 1956, pp. 81-97.

task of discriminating between a vehicle, say, and natural background clutter. Thus, if simple shape recognition is used as the decision criterion, a value of $t_d \approx 1/3$ sec, i.e., the approximate time of a single visual fixation, seems appropriate.

Two estimates for the number of confusing objects, N_c, in Eq. (4) are used. In each estimate the scene is considered to be reduced to an equivalent number of confusing objects randomly distributed in the plane with some given average spacing between objects. In the assumed "low" and "medium" clutter conditions, spacings are 0.1 km, and 0.05 km, respectively. The choice of these two values represents an attempt to bound the clutter problem. There is, of course, no clearly defined procedure for reducing a real scene to a pattern of distinct clutter objects which will require inspection by an observer as he searches for the target. If a tree or a clump of bushes can be confused with a target, then the above values must be regarded as being conservative.

From another point of view, one can argue that the use of an imaging sensor and an observer only makes sense if the spacing between clutter objects is of the order of the uncertainty in the target's position. If this were not so, any simple device capable of sensing some attribute of the target would be sufficient for acquisition. In other words, if a device is pointed in the general vicinity of the predicted position of a target, and if there are no confusing objects in that vicinity, any signal above the noise can be considered a highly probable indication of the target. Thus, the necessity for an imaging sensor and an observer for target acquisition ipso facto implies false targets in the vicinity of the predicted target position.

PROBABILITY THAT OBSERVER IS CAPABLE OF DETECTING TARGET

Experiments by Johnson have established criteria for detection, recognition, and identification in terms of the number of resolvable lines across the target's minimum dimension.[8] Following Johnson's usage; *detection* occurs when an object of potential military interest but of undetermined class membership is said to be present, *recognition* occurs when the class membership of the object is decided, and *identification* occurs when the particular member of the class is decided. Tables of the observed probability of detection, recognition, and identification as a function of the number of resolved lines across the target's minimum dimension have been published by Ratches.[9] Good empirical curve fits to the tabulated values are given by an expression of the form

$$P_D = 1 - e^{-(N/N_o)^2} \tag{5}$$

where N is the number of resolved lines across the target's minimum dimension, and N_o assumes the values of 2.4, 8.4, and 15.4 corresponding to detection, recognition, and identification, respectively. A graphical representation of this expression is shown in Fig. 2. Thus, a stated result for the probability of recognition, for example,

[8] Johnson, J., *Analytical Description of Night Vision Devices*, Proc. of the Seminar on Direct Viewing Electro-Optical Aids to Night Vision, L. Biberman, Editor, Institute for Defense Analyses Study S254, October 1966.

[9] Ratches, J. A., et al., *Night Vision Laboratory Static Performance Model for Thermal Viewing Systems*, AD-A011 212, Army Electronics Command, Fort Monmouth, New Jersey, April 1975.

immediately implies corresponding values of the probability of detection and identification.

Imaging Sensor Performance

If the sensor achieves an angular resolution α at a range R, then the number of resolved lines for a target of width x_T is

$$N = \frac{x_T}{\alpha R} \quad (6)$$

The resolution achieved by the sensor depends upon the apparent temperature of the target and the transmission of the intervening atmosphere. Various methods for calculating the resolution expressed as a minimum resolvable temperature (MRT) are summarized by Decker.[10] The agreement of calculated results with the results of experiments is only fair. Hence, analytical predictions of the resolution achieved by a sensor as a function of the range and environment are to be regarded as first order estimates only. The analytical results described here are based upon a methodology which is most similar to that of Barhydt as described by Decker. A hypothetical FLIR sensor is assumed together with estimates of the target's equivalent blackbody temperature. The assumed sensor and target characteristics together with all of the other parameters used to generate the results to be presented are listed in Table 1 for convenient reference.

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[10] Decker, P. R., *An Experimental Investigation of the Minimum Resolvable Temperature (MRT) Difference Test and Comparison with Mathematical Models*, NWC TP 5890, Naval Weapons Center, China Lake, California, July 1976.

Estimates of the probability of recognition as a function of the range for the hypothetical FLIR sensor assumed here are shown in Fig. 3. The uppermost curve shows the performance of the sensor in vacuum, the middle curve shows the minimum performance that one would expect in the Berlin area about 50 percent of the time, and the bottom curve shows the minimum performance that one would expect to achieve about 90 percent of the time. Since the 90 percent curve includes worse weather than that included in the 50 percent curve, the expected performance is worse.

III. CALCULATED RESULTS

Before describing the results of the present analysis, it is important to remark that the performance curves shown in Fig. 3 pertain to the *static* performance of a FLIR sensor. The curves assume that the observer is looking at the target on the display and is asked to decide its class membership. In a *dynamic* environment, the preconditions for recognition (viz., target in the sensor's field of view, a clear line-of-sight to the target, and an observer fixing his attention on it in the available time) are all-important. The probability of acquisition when these factors are considered will generally be significantly less than that achieved under static conditions.

Single Target Scenario

When the observer's task is to find a specific target at an approximately known position, he uses a *localized search mode* in which the sensor is scanned in the vicinity of the predicted target position. There is a theoretical optimum area which an intelligent observer would search, given the uncertainty in the target's location, the clutter density, and the available time. The calculated values of the probability of acquisition which are presented here assume this optimum search behavior. The basic results are in the form of the cumulative probability of acquisition as a function of the range, i.e., the probability that the observer has found and recognized the target at or before reaching a particular range-to-go.

Figure 4 shows the calculated results for 50 percent Berlin weather, 500 kts aircraft velocity, 0.1 km rms uncertainty in the target's

position, an unmasking range of 6 km, and the two assumed clutter conditions. The two upper curves show the performance of the sensor in vacuum and in 50 percent weather, respectively, under static conditions, i.e., when no search is required. The lower two curves show the probability of acquisition when the optimum search process is included in the calculations. Thus, there is a significant difference in the acquisition probabilities achieved under dynamic versus static conditions. For the medium clutter condition there is approximately a 10 percent probability that the target will not be acquired at all in a single pass. Since a fixed unmasking range is assumed, the acquisition probabilities shown in Fig. 4 are independent of the aircraft's altitude. It is to be noted, however, that according to Fig. 1, an unmasking range of 6 km occurs about 50 percent of the time when the aircraft's altitude is 500 ft, and only about 25 percent of the time when it is at 200 ft. Thus, the limiting effects of the aircraft's altitude are not yet evident in the discussion.

The effects of degraded weather with all other factors held constant are shown in Fig. 5. There is a significant reduction in the acquisition probability at long range primarily because of the decreased performance of the sensor. The acquisition probability at very short ranges, however, is only slightly reduced.

The effect of reducing the aircraft's velocity to 300 kts as compared to 500 kts is shown in Fig. 6. Since a slower aircraft velocity provides more time to search, the probability of acquisition is somewhat higher. The improvement, however, is relatively small. This suggests that the assumed search process is fairly efficient,

i.e., the observer approaches asymptotic search performance well before reaching zero range. This is well illustrated by the results shown in Fig. 7. This figure shows the effect of the unmasking range with all other factors held fixed. The acquisition probability for an unmasking range of 3 km quickly approaches its asymptotic value at short range. In fact, its asymptote is only slightly less than that for a 6 km unmasking range. The acquisition probability for an unmasking range of 9 km is essentially the same as that for 6 km. In this case, the increased search time is associated with the long range performance of the sensor. At long range, the sensor provides little useful information so that the increased search time is of almost no use to an observer.

The effect of the aircraft's altitude is shown in Fig. 8. These curves show the average probability of acquisition weighted by the probability of a clear line-of-sight, i.e., the probability that the target is unmasked at any given range. Once the target is unmasked, it is assumed to remain unmasked at all shorter ranges. Thus, when all unmasking ranges are considered, the probability of acquisition at low altitude is markedly less than any of the results shown previously. The facts that the dependence upon the aircraft's velocity is relatively small, and that the acquisition probabilities at very short range approach the results for a 6 km unmasking range, are consistent with the interpretation that a fairly efficient search is made in the available time. The main effect of the terrain masking associated with low altitude flight is in limiting the sensor's performance to relatively short ranges. Thus, for the assumed environment, there are relatively

few times that the long range recognition capability of a high resolution sensor can actually be realized.

Multiple Target Scenario

As mentioned previously, the sensor is assumed to be used in a staring "pushbroom" sweep search mode in the multiple target scenario. The acquisition probability for 50 percent Berlin weather, 500 kts aircraft velocity, 0.1 km average target spacing, 6 km unmasking range, and the two assumed clutter conditions is shown in Fig. 9. As before, the upper two curves show the static performance of the sensor, while the lower two curves include the effects of search. The probability of acquiring a target at long range is approximately the same as for the single target scenario. Since, however, less information concerning the probable location of a target is assumed to be available, the observer's search process is less efficient. As a result, the asymptotic value of the acquisition probability at short range is less than that for the single target scenario. This, of course, merely reflects the fact that the observer does not know when a target is liable to pass through the sensor's field of view, and, therefore, cannot make as thorough a search.

The results for degraded weather are shown in Fig. 10. As in the single target scenario, the long range acquisition probability is affected most. It is worth noting, however, that the asymptotic value of the probability of acquisition is somewhat less than that for 50 percent weather. The explanation lies in the reduced swath width covered by the sensor at short range. The observer would prefer to

concentrate his attention at longer range since the sensor sees a wider swath and there is a greater probability that a target will be encountered. The degraded weather, however, prevents him from doing this. He is forced to concentrate his attention at shorter ranges where recognition is possible, but where there is a smaller probability of encountering a target. The situation could be improved if the observer were equipped with a zoom rather than a fixed field of view sensor, or if he were assumed to scan in azimuth in an attempt to cover a wider swath. Neither of these alternatives has been investigated in the analysis thus far completed.

The increase in the acquisition probability obtained by reducing the aircraft's velocity to 300 kts is shown in Fig. 11. Since sweep search is less efficient than the optimum localized search used in the single target scenario, the increased search time obtained by reducing the velocity results in a more significantly improved acquisition probability.

The dependence of the acquisition probability on the unmasking range is shown in Fig. 12. As before, a 9 km unmasking range offers little improvement as compared to 6 km. The main effect of beginning the search at 3 km is the decreased probability that a target will be encountered in the swath defined by the angular field of view of the sensor. A zoom or scanning sensor would improve the results.

The dependence of the acquisition probability on the altitude is obtained by weighting the results over all possible unmasking ranges. The results are shown in Fig. 13. Thus, there is a relatively low probability that a target will be acquired at long range, and only

about a 50 percent probability that a target will be acquired at all in a single pass. As mentioned above, these results might be considerably improved if either a zoom or scanning sensor were assumed to be used. Nevertheless, it is difficult to avoid the conclusion that terrain masking is a major limiting factor in long range target acquisition.

IV. CONCLUSIONS

If the assumed scenarios, observer search behavior, environmental conditions, and sensor capability are considered to reasonably represent the real world, then we must conclude that first pass strikes against vehicle-size targets will seldom be possible. Although there is a fairly high probability that a target will be seen in a single pass, the sighting range will often be less than 1 km. Considering the risks associated with low altitude maneuvering at night or in poor visibility, conversion to an attack will only be possible when the target happens to lie almost directly in front of the aircraft. A conclusion of this kind, if accepted, has fairly important implications. Hence, a review of the assumptions leading to it is in order.

First of all, we must ask ourselves whether tactical air might reasonably be expected to perform low level missions at night or during degraded visibility conditions. If a *significant* SAM threat is present, low level flight is the preferred tactic. Further, in view of the apparent Soviet emphasis on night operations, night interdiction and battlefield support missions must be assumed.

The two assumed scenarios are highly idealized representations of the real world. The single target scenario is intended to describe a situation in which a target has been found by a ground observer, say, and its position communicated to an approaching tactical aircraft. Thus, relatively good *a priori* target location information is available. The time at which the target is acquired depends upon the range at which the target is unmasked and the number of clutter objects in the vicinity

of the predicted position of the target. The clutter densities assumed in the analysis are arbitrarily chosen to be commensurate with the uncertainty in the target's location. How often such a condition occurs is unknown.

The multiple target scenario is intended to describe a formation of vehicles close to the battle line. However, the analysis takes no account of the many cues such as smoke, dust, movement, etc., that would be present in such a scenario. The use of the pushbroom sweep search mode implies that the observer in the aircraft is unable to obtain or does not choose to use long range cues to plan an attack against a specific suspect target. If such cues are used, the problem becomes similar to the single target scenario, and the basic question reduces to whether the suspect object or something near it turns out to be a bona fide target. The modeling of the multiple scenario in the present analysis is admittedly weak.

As mentioned in the introduction to this paper, the crucial factor in the analysis is the assumed search behavior of the observer. It bears repeating that very little is known about how an observer actually functions. Hence, the analytical results are subject to serious criticism on this point. On the other hand, the search model used in the analysis does not appear to be overly conservative. Although the exponential form of the search law implies a zero memory observer, the psychophysical constant ($k = 7$) implies seven such zero-memory observers independently and simultaneously searching for the target. The time required to find a target under these assumptions is not overly long. According to Eq. (4), if seven objects are present in the field of

view, the observer finds the target with a probability of 63 percent within a single fixation time. The probability increases to 95 percent in three fixation times, i.e., 1 second. At this stage of our knowledge we simply do not know how to model an observer more accurately. Laboratory and field experiments should be performed to better understand the observer's search process.

The effects of terrain masking appear to be an important limiting factor in the target acquisition process. The data used in the computations are based upon a limited sample of United States terrain thought to be similar to that of North Central Europe. Whether a larger sample of terrain data in the specific area of interest would result in significantly different statistics is unknown.

The hypothetical FLIR sensor assumed in this analysis is somewhat modest in comparison to the best that can be achieved under static conditions. However, the analysis suggests that little improvement would be realized with a better sensor. A more optimistic estimate of the acquisition probability must be based upon a more optimistic quantification of the observer's search problem.

The weather, according to the present analysis, is not the dominant limiting factor in target acquisition. To be sure, poor weather makes the problem more difficult, but the acquisition probability is discouragingly low even for good weather. Low altitude clouds, however, have not been considered.

In summary, many of the assumptions used in the analysis are open to criticism. Yet, no single assumption seems so far removed from

reality as to invalidate the entire analysis. The results challenge the belief that low level tactical missions can be performed effectively at night or in poor visibility conditions. Further analysis and experiments are needed to establish the true situation.

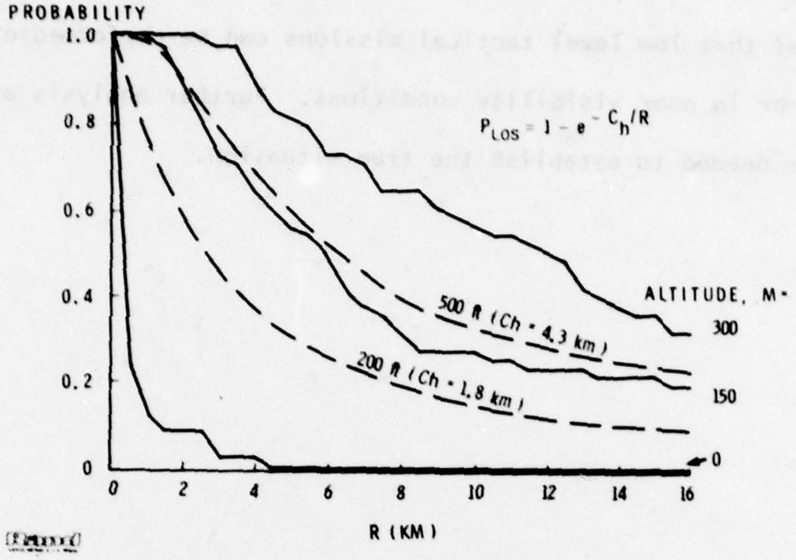

Fig. 1--LOS vs altitude for gently rolling farmland with close forests

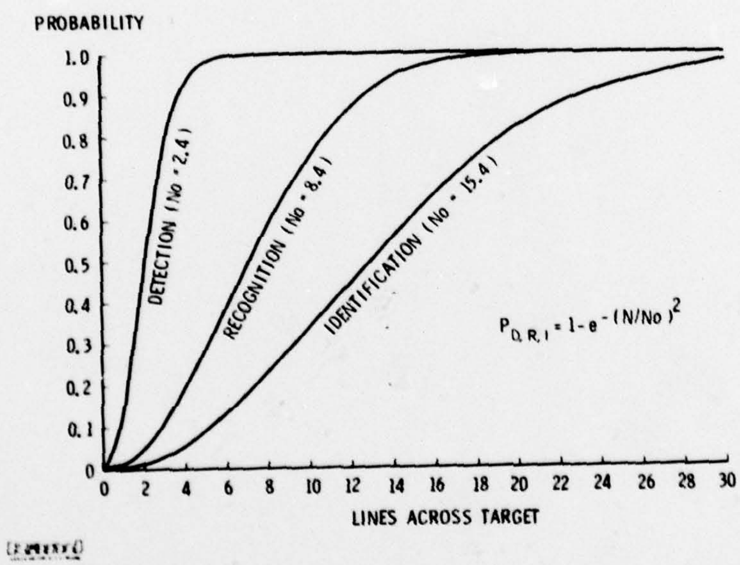

Fig. 2--Detection, recognition, identification requirements

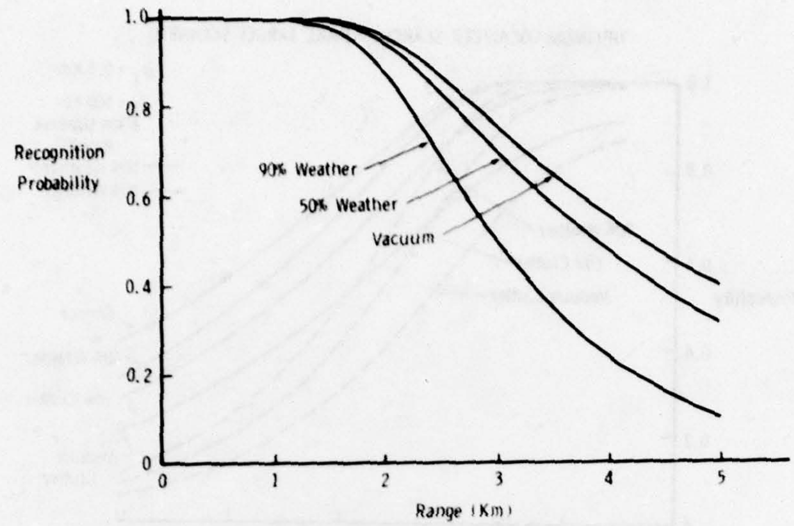

Fig. 3--Sensor performance vs range and weather

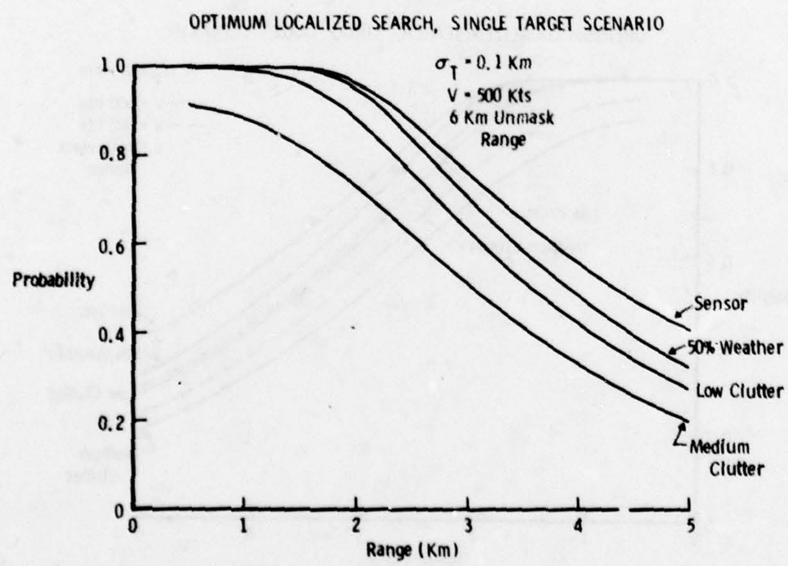

Fig. 4--Acquisition Probability

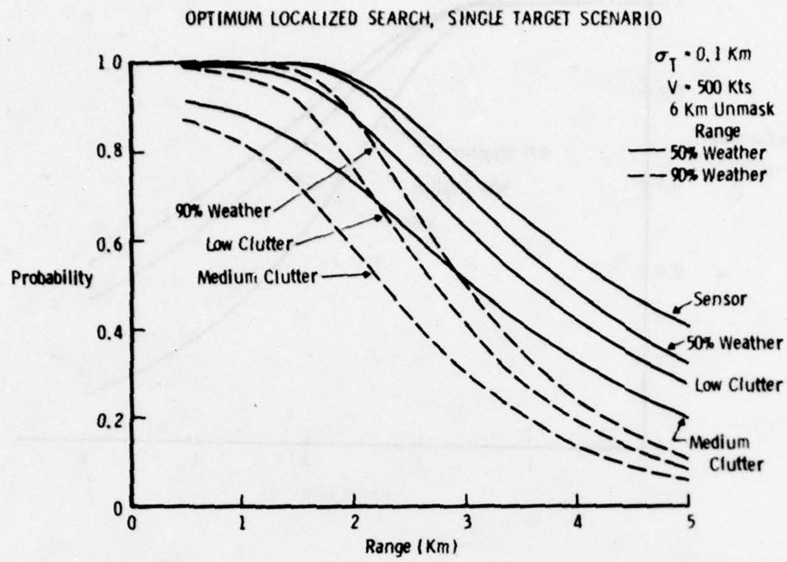

Fig. 5--Acquisition probability vs weather

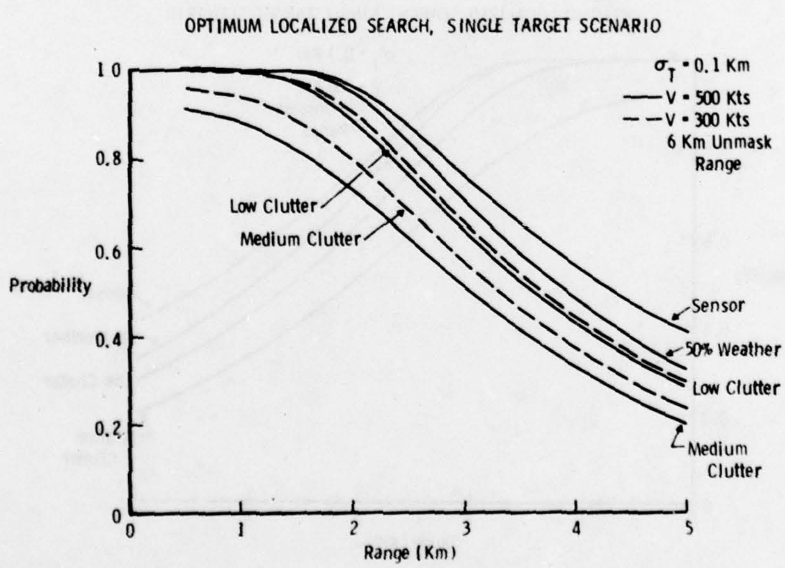

Fig. 6--Acquisition probability vs velocity

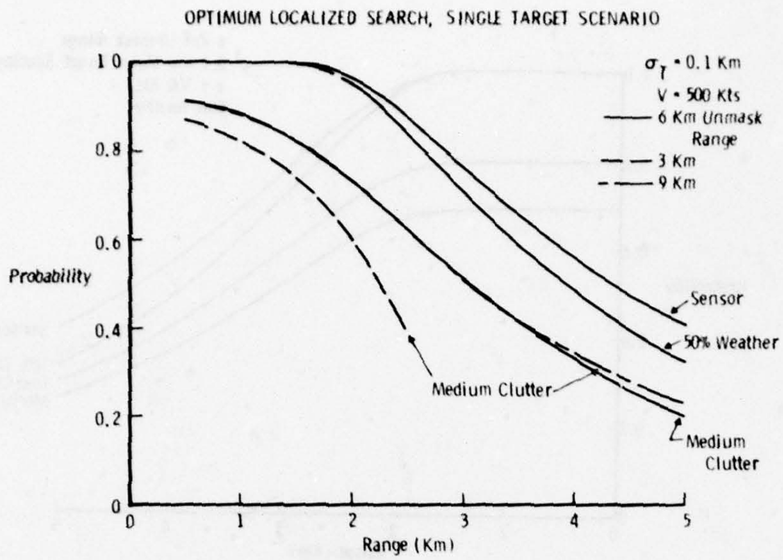

Fig. 7--Acquisition probability vs unmask range

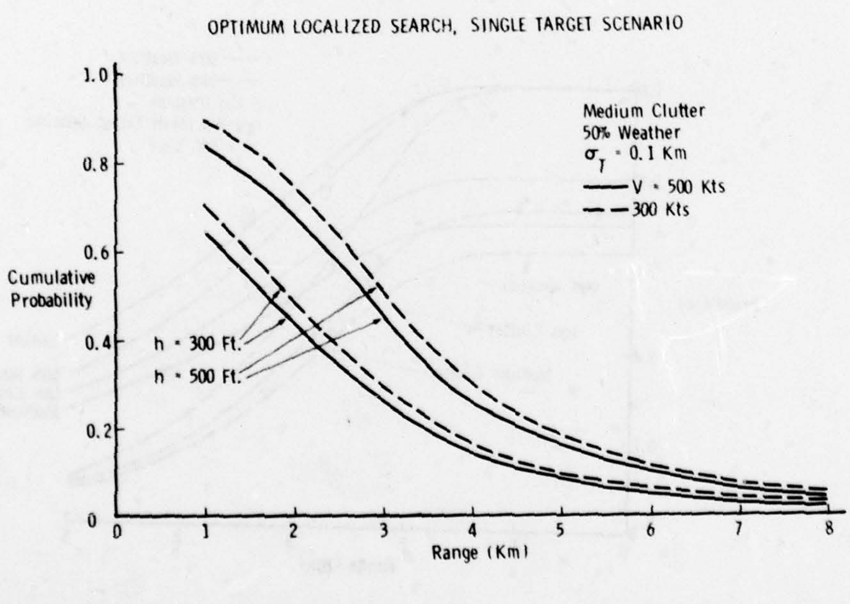

Fig. 8--Acquisition probability vs altitude

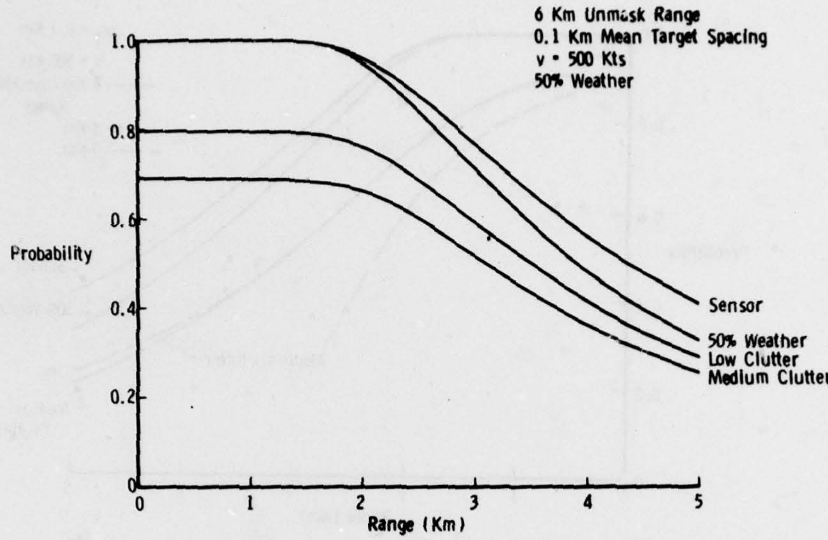

Fig. 9--Probability for acquisition for sweep search multiple target scenario

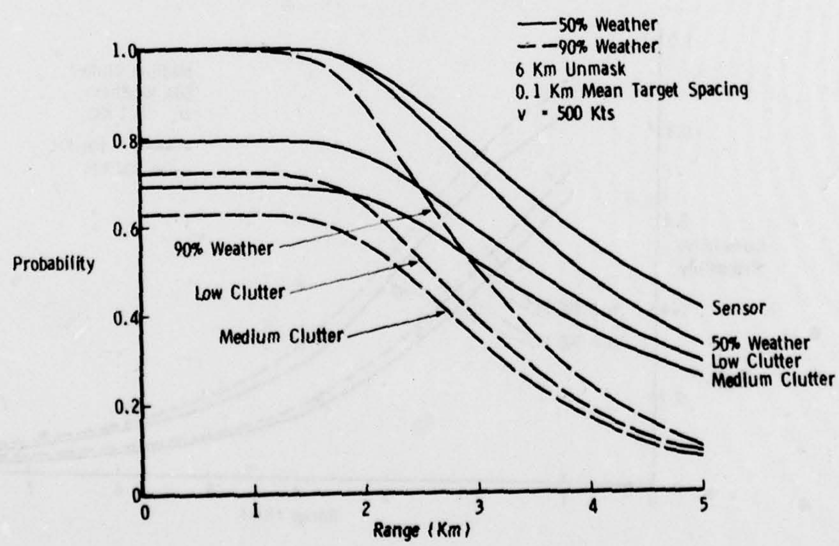

Fig. 10--Probability of acquisition vs weather sweep search multiple target scenario

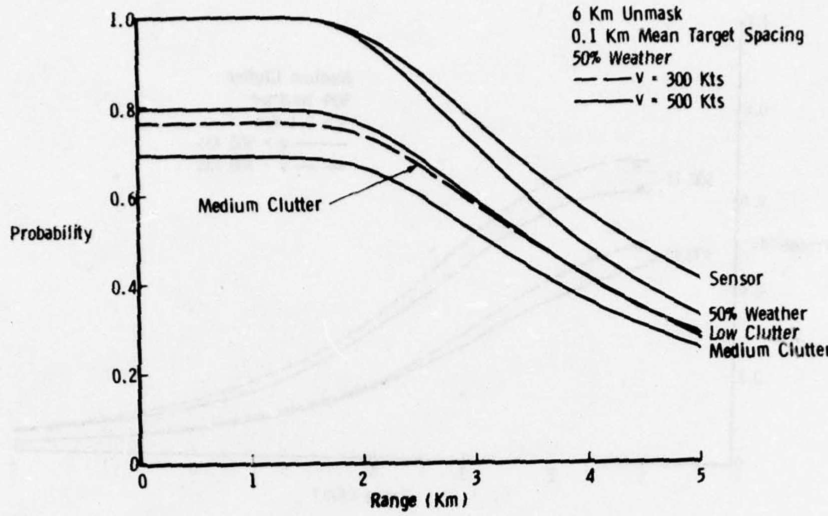

Fig. 11--Probability of acquisition vs velocity sweep search, multiple target scenario

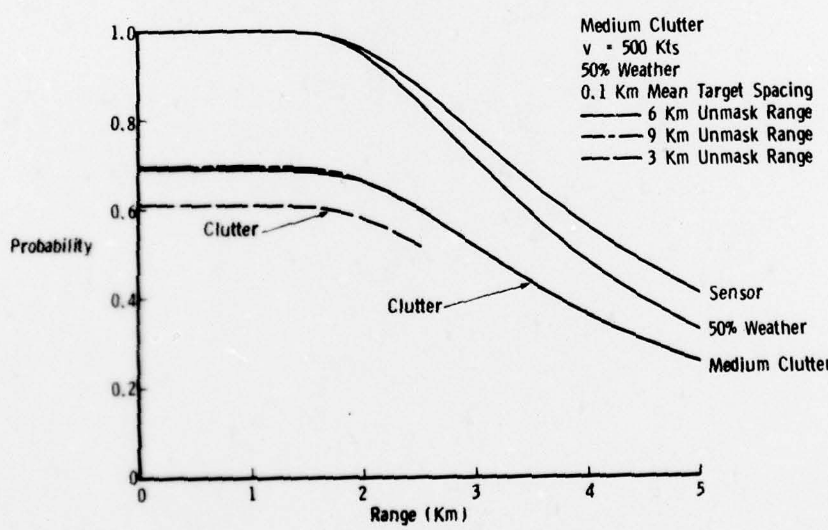

Fig. 12--Probability of acquisition vs unmask range, sweep search, multiple target scenario

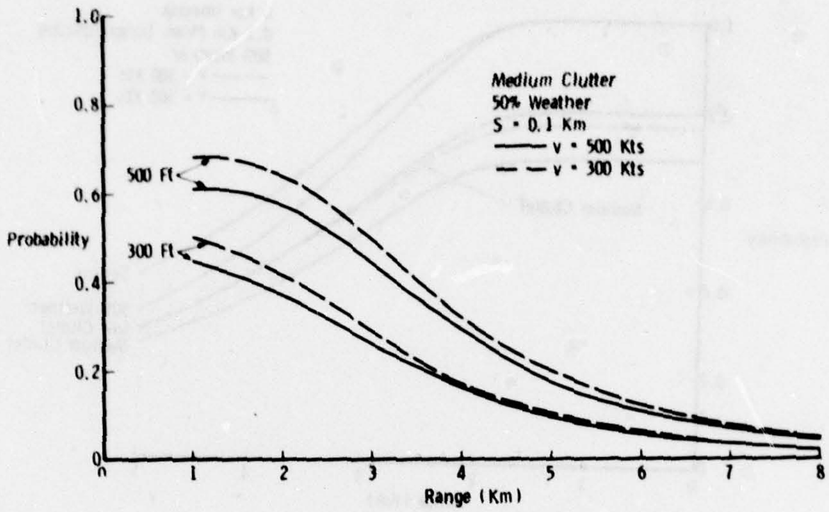

Fig. 13--Probability of acquisition vs altitude sweep search, multiple target scenario

Table 1

PARAMETER LIST

Symbol	Definition	Units	Values
(NETD)	Noise Equivalent Temperature Difference	deg C	0.15
α_D	Detector Subtense	mr	0.15
t_F	Sensor Frame Time	sec	1/30
t_I	Observer Integration Time	sec	1/3
t_D	Observer Decision Time	sec	1/3
α_F	Azimuthal Field of View	deg	2.5
ε	Horizontal to Vertical FOV Ratio	none	4/3
ΔT	Incremental Target Temperature	deg C	5
x_T	Minimum Target Diameter	m	2.3
σ_A	Atmospheric Extinction Coefficient; 50%, 90% Weather	km^{-1}	0.18 0.65
k	Parallel Observation Channels	none	7
N_o	Lines for Recognition	none	8.4
c_h	Line-of-Sight Factor; 200 ft, 500 ft Altitude	km	1.8, 4.3
h	Altitude	ft	200, 500
v	Velocity	kts	300, 500
n	Clutter Density; Low, Medium, High	km^{-2}	100, 400, 1600
σ_y	RMS Target Location Uncertainty	km	0.1
S	Mean Target Separation	km	0.1